First Report from the FORUM Heat Flux Measurement Working Group June 21, 2002

I. INTRODUCTION

The FORUM Heat Flux Measurement Working Group was formed in July 2000 during a working meeting entitled The *Heat Flux Measurement Planning Session* held in Garston, England. A report describing the discussions, conclusions, and recommendations of this organizational meeting is available.

The Working Group operates under the auspices of the FORUM for International Cooperation in Fire Research. Its membership consists of all Forum laboratories that wish to participate. Its mission statement reads:

Promote mutual confidence in flame heat flux measurements and calibrations of heat flux gauges among Forum laboratories.

The following objectives were adopted by the Planning Session participants in order to fulfill this mission statement:

1. Completion of a round robin of heat flux gauge calibrations to allow an assessment of interlaboratory consistency.

2. Recommendation of secondary heat flux standards for use in all Forum laboratories (quantifiable uncertainty).

3. Characterization of heat flux gauge paints.

4. Interlaboratory comparison of applied heat flux calibrations in standard flammability apparatuses (e.g., cone calorimeter) using various types of heat flux gauges, including slug calorimeters.

5. Interlaboratory comparison of heat flux measurements at specified locations under defined conditions for standard flaming fire tests (e.g., ISO 5660 and ISO 9705).

The participants agreed to carry out a number of activities during the year just past. The primary cooperative effort was the completion of an informal round robin designed to assess agreement between the various approaches for heat flux calibration used in the various laboratories. Additionally, individual laboratories committed to providing additional information, research, and support activities designed to contribute to the Working Group mission statement.

The list of activities proposed by the individual laboratories follows:

- SP-Sweden will continue work on the Gunner's gauge and initiate work on the development of a slug calorimeter for heat flux measurements during flooring tests.

- FM Global researchers will provide a written description of their primary standard and heat flux gauge calibration procedures.

- Sintef will provide documentation concerning uncertainties identified in their heat flux gauge calibration procedures.

- BRE/FRS will provide historical documentation (including internal documents) concerning the development of primary standards and heat flux gauge calibration.

- Research Institute, State Key Laboratory of Fire Science will make available calibration data for several heat flux gauges along with results of recalibration as they become available.

- NIST will continue to coordinate the activities of the FORUM Heat Flux Measurement Working Group and provide documentation concerning the NIST primary heat flux standard and details concerning commercial calibration activities at NIST.

It was decided that the next meeting of the Working Group would be held in Edinburgh in September, 2001 in conjunction with the Interflam2001 meeting. This meeting was subsequently scheduled for September 14-15, 2001 at Heriot Watt University. The Working Group is particularly thankful to Carole Franks of Interscience Communications who provided invaluable assistance in making the necessary arrangements. On September 11th the world was shocked by the coordinated terrorist attack on the United States. All of the working group members express their sorrow and outrage over these events. The disruption, both general and particularly in air service, necessitated that the meeting in Edinburgh be postponed.

In order to allow a meeting prior to the FORUM annual meeting in October, it was necessary to reschedule the working group meeting in a short period of time. Fortunately, Ingrid Wetterlund and Ulf Wickström of SP-Sweden volunteered to host the meeting in Boräs in conjunction with a number of ISO committee meetings and a meeting of the EU HFCAL project. The Working Group gratefully accepted this offer, and the meeting was held on October 8-9, 2001. The entire Working Group thanks Ingrid and Ulf for their flexibility and kind hospitality.

The annual meeting was attended by representatives from five of the six FORUM laboratories that participated in the original planning session. A list of participants is included as Appendix A. A representative from the Research Institute, State Key Laboratory of Fire Science was unable to attend, but a written activity report was submitted and is included below. It should be noted that representatives from two laboratories (VTT and Underwriter Laboratories) not present at the planning session were scheduled to attend the cancelled meeting in Edinburgh. The Working Group invites these laboratories to join us in the future. This report, based on the results of this meeting, summarizes the activities, conclusions, and planning activities of the Working Group during the period from July 2000 to October, 2001.

II. WORKING GROUP ROUND ROBIN

IIa. Round Robin Design

During the planning session it was recognized that Forum laboratories utilized a variety of independently developed approaches for in-house calibration of heat flux gauges. An informal round robin designed to assess the degree of agreement between calibrations by the various laboratories was organized under the direction of Debbie Smith of BRE/FRS and was carried out during the past year.

Two commercial heat flux gauges, a 2.54 cm Gardon gauge and a 1.27 cm Schmidt-Boelter gauge, procured by NIST/BFRL were used for the round robin. The nominal full-scale ranges for both gauges were 100 kW/m^2. Embedded thermocouples were provided to measure the body and surface temperatures of the gauges. The gauges were shipped in a foam-rubber-lined case along with a thermocouple reader.

The *pattern* (nomenclature utilized here is taken from the *Guide for Interlaboratory Comparisons*, Recommended Practice RP-15, National Conference of Standards Laboratories, March, 1999) was the "basic circular" in which these gauges were first calibrated by a "pivot" laboratory, in this case NIST/BFRL and then sent sequentially to the other participating laboratories. At the completion of the circle the gauges were returned to NIST for recalibration to check that travel and handling had not measurably shifted the responses of the two gauges.

Each laboratory was asked to calibrate the two gauges using the method they routinely employed. They were also asked to record the two thermocouple "surface" and "body" temperatures at the time of the measurements. Subsequent to their calibrations each laboratory provided a short description of their heat flux gauge calibration facility.

IIb. Laboratory Calibration Facilities

BRE/FRS

The calibration of radiometers for use as working standards is carried out by comparing radiometer response at various levels of irradiance with the response of a secondary standard radiometer at the same levels of irradiance. The measurements are made at different levels of irradiance by varying the distance between the radiant source and the radiometers.

The radiant source is a 0.3 m by 0.3 m porous refractory burner fueled with natural gas and air. It is mounted vertically and is operated in the temperature range of 800 °C to 1000 °C.

Both the secondary standard radiometer and the instrument to be calibrated are mounted side-by-side on a sliding frame and moved into the measuring position, in turn. A schematic diagram of the apparatus is shown in Fig. 1.

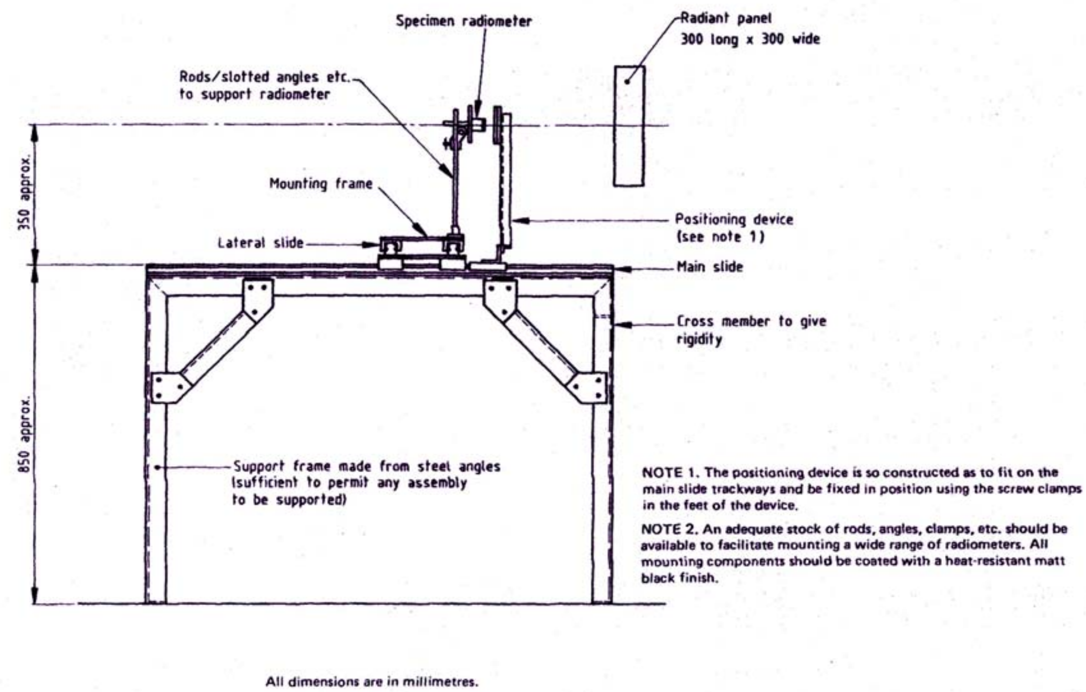


Figure 1. Schematic for the BRE/FRS heat flux gage calibration facility.

FM GLOBAL

FM Global calibrates its gages by placing them at several different distances in front of a hot furnace orifice that emits a known heat flux. Figure 2 illustrates the method of calibration. It is a direct calibration based on first principles rather than a transfer from some other device.

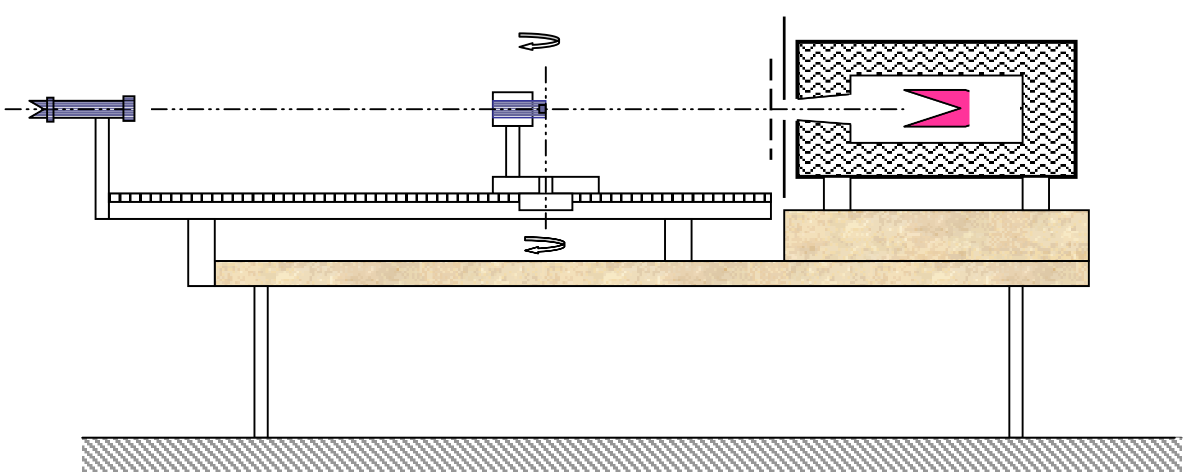


Figure 2. Schematic of the FM Global calibration approach.

The same apparatus is used to measure the *angular* sensitivity of different gage coatings. In general the angular sensitivities of coatings are not Lambertian (i.e. do not follow a cosine law) and therefore must be measured. Measurements have been provided for the angular sensitivities of the round robin Schmidt-Boelter and Gardon gages as well as Gardon gages having Thurmalox and IITRI MH2IIP coatings.

NIST

The NIST heat flux gage calibration system was assembled in the mid 1970s. It has recently been described in a NIST Report of Test (*NIST/BFRL Calibration System for Heat-Flux Gages*, FR 4014, August 6, 2001).

The heat source consists of a commercial radiant heater incorporating a 2000 W tungsten-halogen filament lamp. The lamp is placed at one of the foci of a large ellipsoidal reflector, with the entrance to a kaleidoscope flux redistributor (see below) at the other. The distance between the foci is roughly 30.5 cm. A metal housing surrounds the half of the ellipsoidal mirror containing the lamp. The mirror passes through the wall of the housing and extends 10 cm before being cut off short of the second focus of the ellipse. The lamp housing with extended mirror can be seen in the photograph included as Fig. 3.

A blackened radiation shield with a 6.4 cm wide × 6.4 cm high square cut out centered on the mirror axis is positioned 2.5 cm from the mirror. A small box, open at both ends, is attached

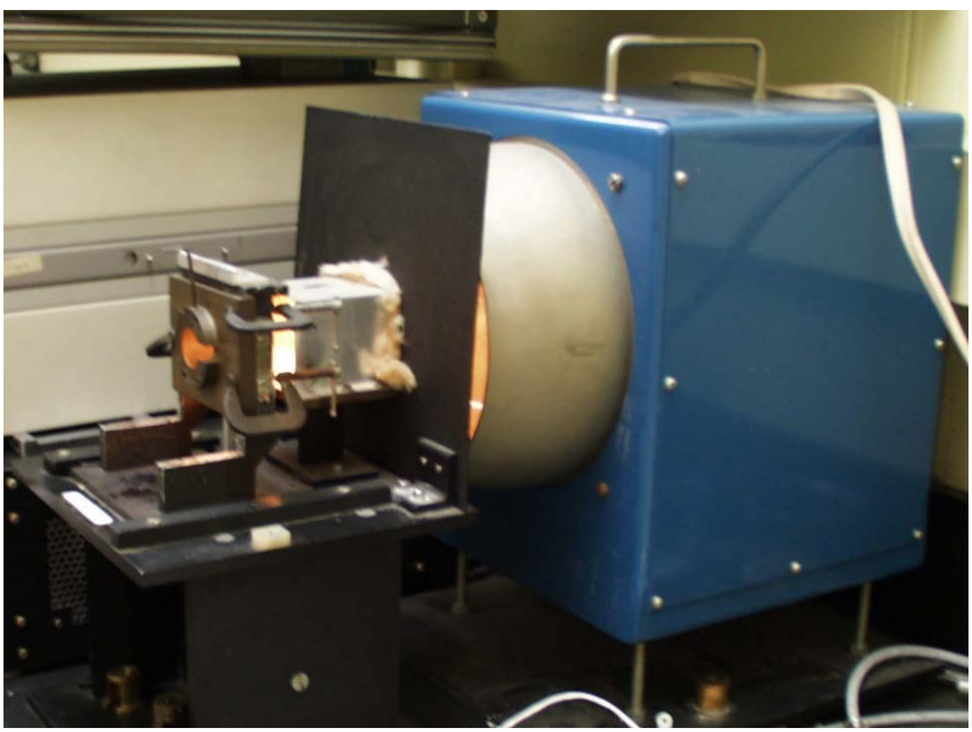


Figure 3. Photograph of the NIST heat-flux gage calibration facility.

over the radiation shield cut out on the side opposite the lamp. (see Fig. 3) Its length is roughly 7.6 cm. The interior of the box provides internal reflections of light that redistribute the energy flux by forming and superimposing multiple images such that the flux distribution becomes more uniform at the exit, similar to the multiple images formed by a kaleidoscope. The gage to be characterized is positioned at a reproducible location on the far side of the kaleidoscope flux redistributor using an especially designed mount.

Heat flux calibrations are performed using a secondary-standard heat flux gauge that was calibrated by the Radiometric Physics Division of the National Bureau of Standards. An arbitrary heat flux level is set by adjusting the lamp power supply voltage and current, and the lamp is allowed to stabilize (generally 20 min). At this point the response (voltage output) of the secondary-standard heat flux gage is recorded. The secondary standard is then replaced with the gage to be tested and the response is again recorded. Once a calibration cycle is completed, the lamp output is readjusted to another flux level, and, following a stabilization period, the entire measurement procedure is repeated. Generally, four flux levels over the 0 kw/m^2 to 15 kW/m^2 range are utilized. Following the completion of a calibration the results are plotted as imposed heat flux (kW/m^2) versus the corresponding gage output readings in mV. A linear least squares curve is employed to fit the experimental data points, and the result is reported in terms of kW/m^2 per millivolt.

SINTEF

Calibration of heat flux meters is performed using a spherical furnace (Fig. 4) with a small opening and is normally considered calibration by a primary reference. The radiation in this opening is defined closely by the temperature of the inside surface and the Stefan-Bolzman equation. The radiation angular dependence is considered constant for the full 180° view inwards from the opening. Radiation levels can be obtained from 0 to 200 kW/m^2 by varying the temperature up to 1100 °C.

The calibration is performed by first inserting a reference flux meter and measuring the signal. The unknown flux meter is then inserted and measured in the same way. At the same time a reference thermocouple inside the furnace measures the temperature in order to determine the furnace radiation heat flux level.

The reference flux meter and the reference thermocouple are used to determine both radiation level and convection level inside the furnace. The calculation of the flux meters' convective component is based on the assumption that the reference and test flux meters have similar convective characteristics.

The temperature of cooling water representing the temperature of the flux meter bodies is also measured in order to determine the net flux level to the heat flux meter.

SP

The calibrations were performed according to NT FIRE 050. The method is mainly intended for calibration of total heat flux meters of the Gardon and Schmidt-Boelter types. The method

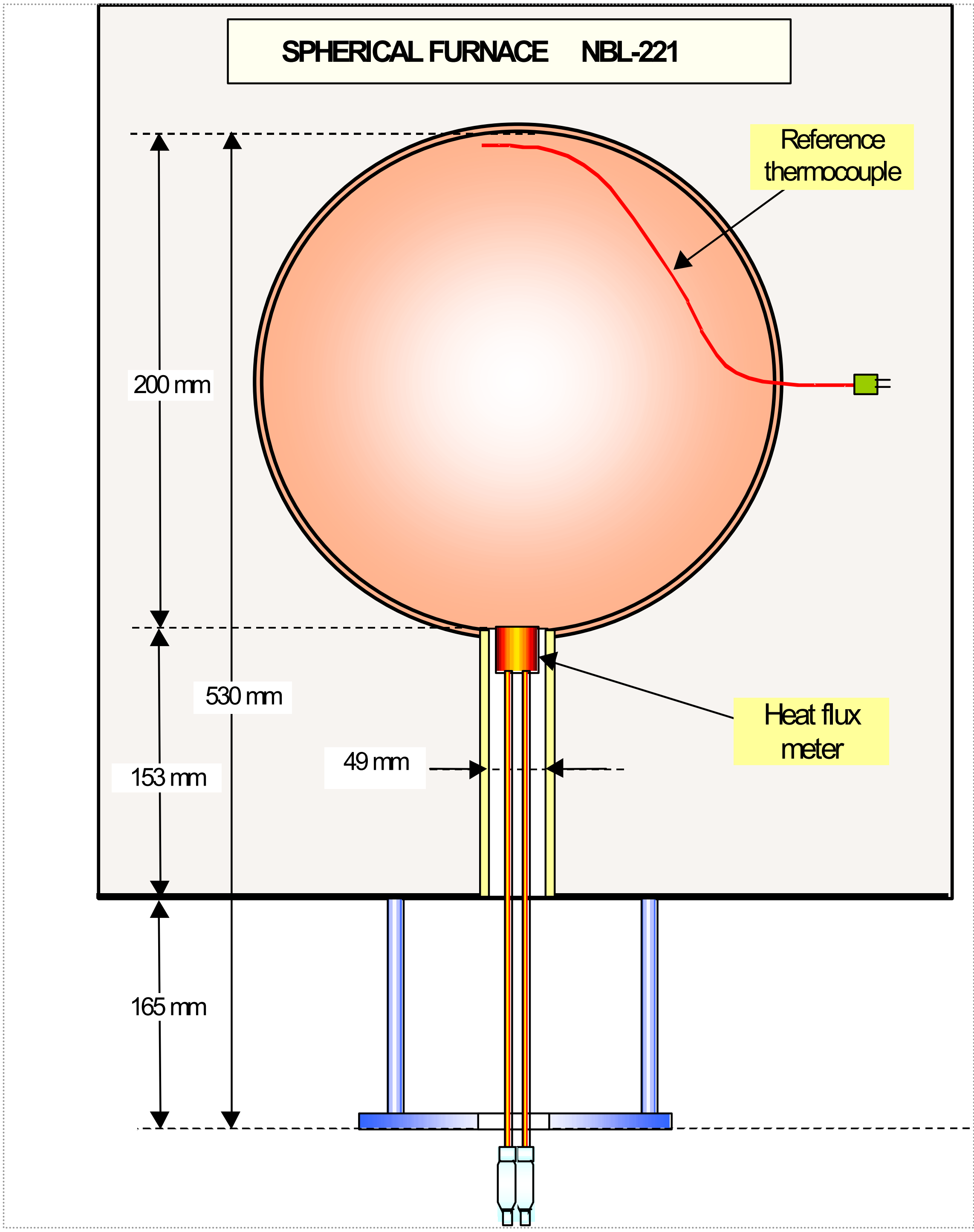


Figure 4. Scematic of the SINTEF heat flux gauge calibration facility.

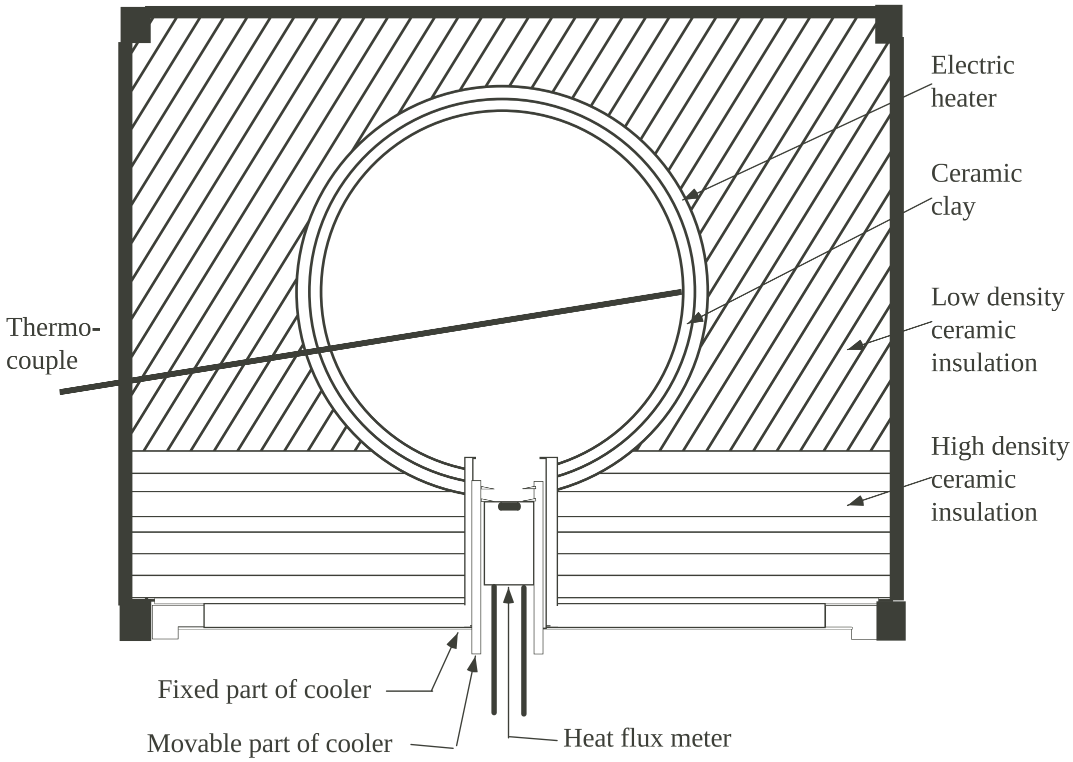


Figure 5. Drawing of the SP heat-flux gage calibration facility.

enables calibration from 2 to 100 kW/m^2. Heat flux meters with a housing diameter of up to 50 mm and a sensitive area diameter of up to 10 mm can be accommodated.

The method consists of a blackbody radiation source designed as a well-insulated, electrically heated spherical furnace chamber with an aperture at the bottom, shown in Fig. 5. The temperature of the furnace is accurately controlled and is rather uniform inside the furnace, assuring a high precision measurement of the radiation level. The method has an uncertainty equal to or less than ± 3.0 % with 95 % confidence.

A cooling device housing the heat flux meter is inserted in the opening at the bottom of the furnace. The inside diameter of the furnace is larger than 4.5 times the restricting aperture of the fixed cooler at the bottom of the furnace. The aperture in the cooling device defines the view factor under which the furnace radiates to the heat flux meter.

Heat flux meters to be calibrated are inserted through the aperture with the sensing surface of the heat flux meter oriented horizontally. The influence of convection is thus greatly reduced. The cooler insert has a number of shields, which protect the gauge from receiving radiation reflected from the cooler wall. The shields help to maintain the stratification of air so that convective airflow is minimized. The heat flux meter sees nothing but the controlled environment of the blackbody emitter. The radiation level of this blackbody emitter depends solely on the measured temperature, making it traceable to international thermal calibration standards.

The calibration is performed at 10 flux levels, evenly distributed over a temperature range from 400 °C to a temperature corresponding to the maximum flux level of the gauge. Before the heat flux gauge is mounted in the cooling device, the radius of the sensing element is measured. In the case of the FORUM round robin the information about the radius was received from the manufacturer of the gauges. The distance between the top of movable cooler and the receiving sensor of the heat flux meter is also measured. Both of these dimensions are used as input for calculating the view factor. When the temperature is stable within ±1 °C/min at the set level, records of the water and the furnace temperature together with the output signal from the gauge are taken over a 1 minute period (approx 120 records).

Summary of Facilities

Table 1 summarizes major characteristics for the various calibration systems used by the participants in the round robin. The type of heat source is indicated along with a general description of the approach used for estimating the fluxes impinging on the heat flux gauge to be calibrated and whether the heat source is limited to angles near the gauge normal or fills the entire field-of-view for the gauge (hemispherical).

IIc. Round Robin Results

Each laboratory reported the results for the calibrations of the two heat-flux gages in terms of the coefficients determined from linear least squares curve fits of the data when plotted as kW/m^2 versus the response of the gauge in mV. In some cases the y-intercept was forced to pass through the plot origin, while in others it was allowed to "float," and a y-intercept value from the fit is reported.

There are many different approaches that might be used to compare the results from different laboratories. The working group decided that two were appropriate. The first is to graphically

Table 1. Radiant Source, Method for Characterizing Heat-Flux Level at Gauge, Incident Angle and Maximum Heat Flux at the Gauge for the Various Heat Flux Gauge Calibration Methods.

Lab	Source	Characterization	Angle	Maximum Applied HF
BRE	Porous Burner	Secondary Standard	Narrow Angle	55 kW/m^2
FM Global	Target in Cylindrical Black Body	Optical Pyrometry	Narrow Angle	1.1 kW/m^2
NIST BFRL	Tungsten Lamp in Ellipsoidal Furnace	Secondary Standard	Narrow Angle	16.5 kW/m^2
SINTEF	Spherical Black Body	Secondary Standard	Hemispherical	98 kW/m^2
SP	Spherical Black Body	Calibrated Thermocouple	Narrow Angle	85 kW/m^2

Table 2. Results of Linear Least Squares Curve Fits to Calibrations for the Schmidt-Boelter Gauge.

Laboratory	y-intercept	Uncertainty	Slope	Uncertainty
1	0.3753	0.0046	9.0554	0.0008
2	-0.40	0.10	8.510	0.025
3	--	--	8.991	0.030
4	--	--	9.415	0.057
5	-0.029	0.022	9.237	0.20
Manufacturer	--	--	8.826	--

compare the calculated lines. Since the y-intercepts are close to zero for those fits where they were allowed to vary, this is nearly the same as comparing the slopes for the lines. The second method was to compare the heat-flux reading corresponding to the nominal-full scale voltage outputs (10 mV) for the gauges.

For the present, the working group decided that results should be reported without identifying the individual laboratories making the calibrations. For this reason, the results are identified only as laboratories "1" to "5". At the same time the representatives affirmed that the dissemination of data from individual laboratories is at their own discretion following presentation of results to the FORUM Heat Flux Measurement Working Group.

Table 2 lists the calibration results for the Schmidt-Boelter heat flux gauge from the five laboratories as the y-intercept (if allowed to float) and the slope of linear least squares fits of imposed heat flux versus gauge reading in mV. These values are compared with the calibration provided by the manufacturer. Indicated error limits are values determined from the linear least squares fits and represent one standard deviation. Figure 6 shows the results in Table 2 plotted as straight lines. There is an identifiable scatter in the data from the different laboratories, but in general the curves fall close together and agree well with the calibration provided by the manufacturer.

The calibration results for the Gardon gauge have been analyzed in a similar manner. Table 3 lists the y-intercepts (if reported) and slopes of the calibrations along with the calibration result reported by the manufacturer. Corresponding plots are shown in Fig. 7.

For a given heat flux the Gardon gauge generates roughly 25 % less output voltage than the Schmidt-Boelter gauge, even though both gauges have the same nominal full-scale ranges. The calibration curves for both gauges have very similar appearances. For both, the calibration lines determined by the various laboratories fall relatively close together. However, the differences between laboratories are apparently not random. The relative ordering of the lines is nearly the same for both gauges with Laboratory #4 measuring slightly higher responses and Laboratory #2 slightly lower. The results for the three remaining laboratories are intermediate and lie close together. For both gauges the manufacturer's calibration lies just above those for Laboratory #2.

Predicted heat flux values corresponding to a full-scale response are used to provide a more quantitative assessment of the degree of agreement between the calibration results from the five

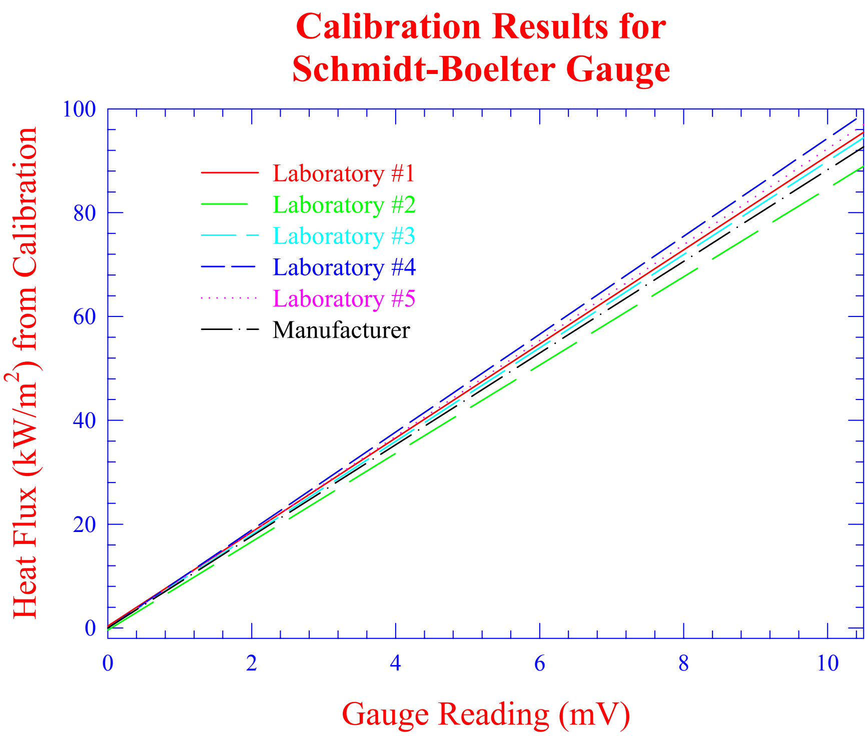


Figure 6. Linear calibration curves for the Schmidt-Boelter heat flux gauge determined by the five laboratories participating in the round robin are shown. The calibration provided by the gauge manufacturer is included for comparison.

Table 3. Results of Linear Least Squares Curve Fits to Calibrations for the Gardon Gauge

Laboratory	y-intercept	Uncertainty	Slope	Uncertainty
1	1.260	0.019	11.917	0.005
2	-0.139	0.041	11.269	0.014
3	--	--	12.240	0.028
4	--	--	12.757	0.040
5	0.048	.040	12.279	0.049
Manufacturer	--	--	11.481	--

laboratories. Figure 8 is a plot of the predicted heat fluxes corresponding to a full-scale voltage output, i.e, 10 mV for the Schmidt-Boelter and Gardon Gauges from the five Forum laboratory calibrations versus the values obtained from the manufacturer's calibration. Error bars are included with the symbols that represent 95 % confidence intervals for the predicted values based on regression analysis of the individual calibration results. In some cases the error bars are smaller than the corresponding symbols.

The five values of calculated heat flux plotted in Fig. 8 have been averaged for each gauge. The averages and standard deviations are 90.4 kW/m^2 ± 3.6 kW/m^2 and 121.1 kW/m^2 ± 5.5 kW/m^2

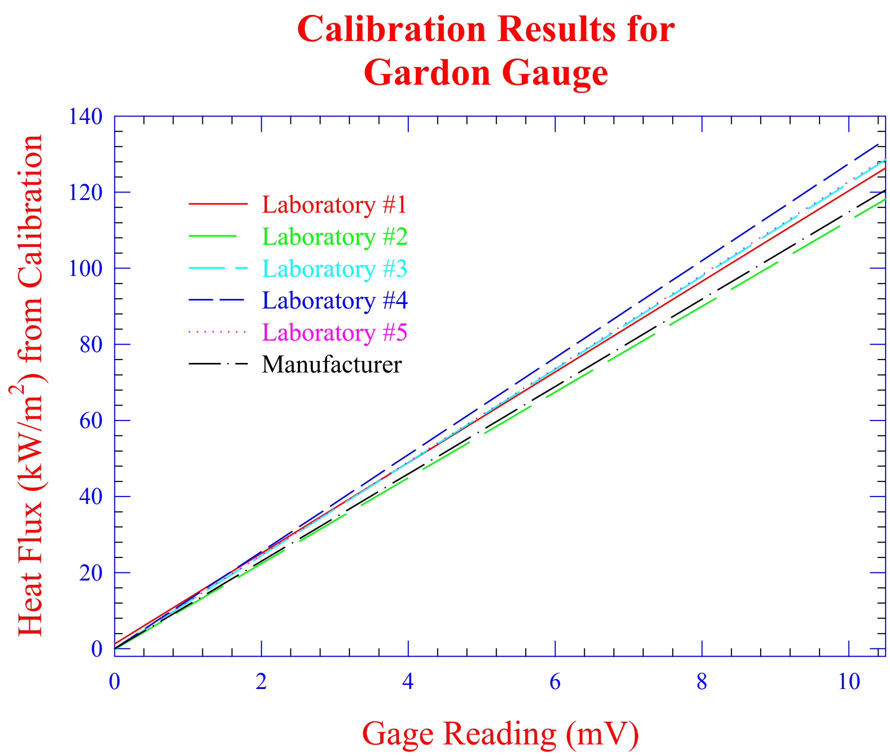


Figure 7. Linear calibration curves for the Gardon heat flux gauge determined by the five laboratories participating in the round robin are shown. The calibration provided by the gauge manufacturer is included for comparison.

for the Schmidt-Boelter and Gardon gauges, respectively. The standard deviations represent 4.0 % and 4.5 % of the two averaged values. The averages can be compared to the corresponding results based on the manufacturer's calibration of 88.3 kW/m^2 and 114.8 kW/m^2.

The last step in the round robin was to demonstrate that the responses for the two gauges were not measurably altered during transport and testing. This was accomplished by recalibrating the gauges in the Building and Fire Research Laboratory at NIST at the end of the round robin. Figure 9 compares data taken during three independent calibrations of the Schmidt-Boelter gauge at the start of the round robin with a fourth calibration recorded when the gauge was returned to NIST following calibration at the four other laboratories. Linear least squares curve fits for both sets of data are included on the plot. The two lines lie nearly on top of one another. In fact, both the y-intercept and slope for the two plots easily agree within the one sigma deviations derived from the linear least squares curve fits. On this basis it concluded that the response of the Schmidt-Boelter gauge was unchanged during the round robin.

Figure 10 shows the corresponding results for the Gardon gauge. The linear least squares curve fits do not agree as well as those found for the Schmidt-Boelter gauge. The resulting slope is 1.4 % higher for the measurements made following the round robin. This value is larger than the uncertainties associated with the fits, but is small compared to the calibration variations observed between the various laboratories. In terms of values extrapolated to the nominal full range of the gauge, this corresponds to a difference of 1.5 kW/m^2.

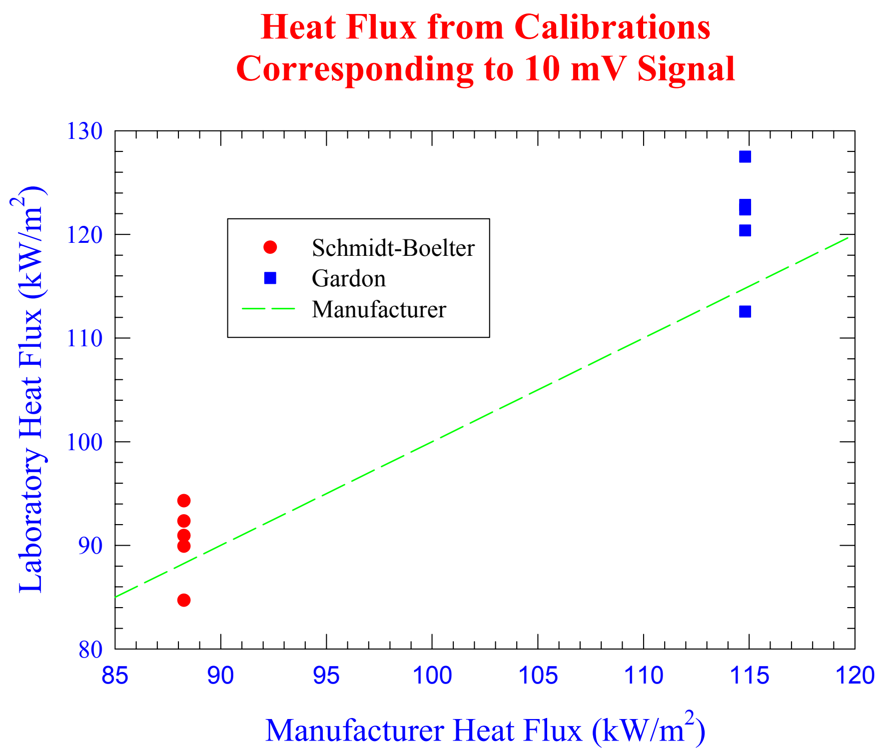


Figure 8. Predicted heat fluxes corresponding to a 10 mV output based on Forum laboratory calibrations for the Schmidt-Boelter and Gardon gauges are plotted as a function of the manufacturer's calibration.

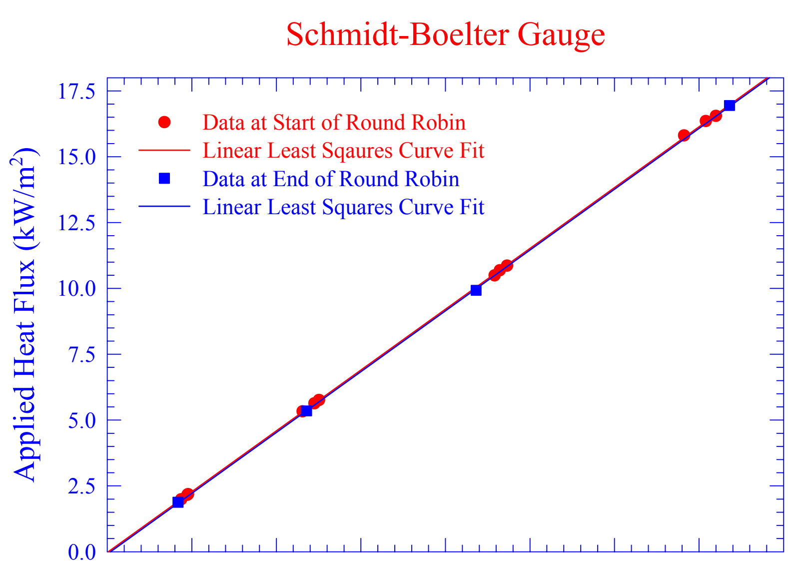


Figure 9. Calibration results recorded at the beginning and end of the round robin are shown for the Schmidt-Boelter gauge. Linear least squares curve fits are included for both sets of data.

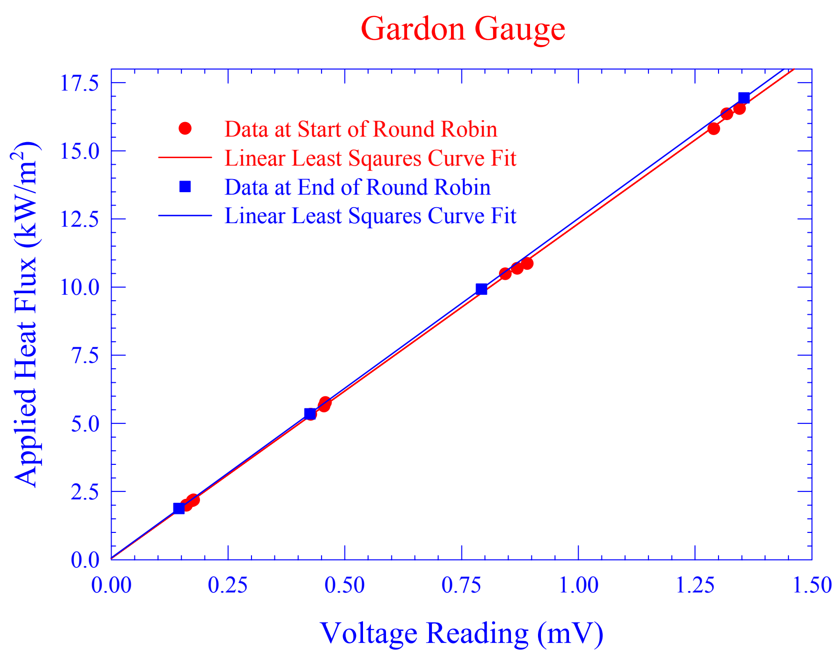


Figure 10. Calibration results recorded at the beginning and end of the round robin are shown for the Gardon gauge. Linear least squares curve fits are included for both sets of data.

IId. Round Robin Discussion

Given the significant differences between the calibration facilities used in the various laboratories, the working group members expressed surprise at the degree of agreement for the calibrations as reflected in the standard deviations from the average values for the nominal full-scale readings of the two gauges. Applying a coverage factor of 2, these deviations are 8 % and 9 % for the Schmidt-Boelter and Gardon gauges, respectively. These ranges are somewhat larger than the uncertainties reported by those laboratories that have provided detailed analyses for absolute uncertainty, but only by a relatively small margin.

As noted above, detailed comparisons show that the variations appear to have systematic distributions for the two gauges. This suggests that calibration repeatability for individual laboratories is much better than indicated by the observed variations and that the variations are the result of true differences among the calibration facilities. There are a number of gauge response and calibration system parameters that might be responsible for the observed systematic variations. Examples of parameters that have the potential to change the response of the heat flux gauges employed here include wave length sensitivity, angular sensitivity, relative responses to convective and radiative heat transfer, and non linear gauge response. A variety of calibration system parameters can also introduce differences. Systems that utilize a secondary standard are linearly sensitive to its calibration. Any variations between the calibration standards between laboratories should appear as differences in the results. Secondary standards have all of the potential sensitivities listed above that can impact the calibrations. Some of the laboratories calibration systems require a number of additional measurements such as black-body temperature, distance from the source, and the angle of the radiative source observed. Any uncertainties in these measurements propagate into the final calibration results. It is worthwhile to emphasize again that given the large number of potential sources of disagreement between the laboratories, the degree of agreement is quite good.

The results allow some analysis of the relative effects of potential error sources. Each laboratory found that their calibration data could be fit to a straight line with high precision. As Table 1 indicates, the amount of extrapolation required to estimate a full-scale heat flux reading varied substantially for the various calibration approaches. Since any nonlinearity in the response will affect the accuracy of such extrapolations, the absence of large variations in the extrapolated values is indicative of a highly linear response for the gauges.

Similarly, due to the wide variety of heat flux sources used (see Table 1), as well as the different heat flux levels for which calibrations were carried out, the temperatures of the various sources used during the calibrations varied over an extensive range both during a given calibration as well as between laboratories. As a result, the wavelength distributions for the sources varied substantially as well. The linear response of the gauges, as well as the ability to substantially extrapolate from the measured results with good agreement between laboratories, indicates that the two gauges have nearly flat wavelength responses.

Similar considerations suggest that the calibrations are relatively insensitive to the angle at which the thermal radiation strikes the gauges. This conclusion is based on the observation that the view factors for the various calibration facilities vary substantially and that for at least one of the calibration facilities (FM Global) the angle is changed during the calibration procedure. A strong sensitivity to the angle of the radiation striking the gauge surface would be expected to appear as substantial differences in the calibration results.

It is important to mention that even though the angles vary substantially between different calibration facilities, with the exception of the SINTEF facility, the irradiation is far from hemispherical. This is indicated in Table 1 where the term "narrow angle" is used. In effect this means that radiation does not strike the gauges at large glancing angles. In work described further below, FM Global evaluated the angular response for the two gauges used in the current study. For angles (θ) varying from 0º (perpendicular to gauge surface) to 86º both gauges displayed an idealized $\cos(\theta)$ response. Since such a response is accounted for in the calibrations, the absence of an angular dependence is reasonable. The SINTEF calibrations are carried out in such a way that thermal radiation strikes the gauge at large values of θ. The FM Global results indicate that the gauges do not obey the $\cos(\theta)$ relation at large angles and, in fact, are less sensitive than would be predicted using this relation. This fall off in sensitivity could lead to 4 % differences in gauge responsivity between narrow angle and hemispherical calibrations.

The gauges are generally calibrated assuming that radiative heating is the only heat transfer process taking place. However, both Gardon and Schmidt-Boelter gauges are known to be sensitive to convective heat transfer as well, which is expected to occur when gas at a temperature different than the gauge surface flows over the gauge. Due to the large differences between the calibration facilities used by the various laboratories, there is the potential for significant variations in the contribution of convective heat transfer to gauge response. The relatively narrow range of calibration results suggests that such effects are no larger than the observed variations between the different approaches. It should be noted that this doesn't necessarily require that convective heat transfer process be absent during a calibration, but only that its effect is cancelled out in some manner. For instance, in experiments utilizing secondary-standard gauges, the convective component will have no effect on the calibration if it makes the same contribution as for the gauge being calibrated.

To summarize. Differences between calibration results for the Forum laboratories participating in the round robin were systematic and were somewhat larger than can be explained simply by statistical uncertainties in the calibrations. While distinguishable, these differences are viewed as being surprisingly small given the wide range of calibration approaches employed. A number of potential sources for the differences have been discussed. The use of secondary standards and convective heat transfer effects appear to offer potential explanations. Nonlinear gauge response, wavelength response variations, and angular dependence would seem to be less important.

III. Related Activities Performed by the Participating Laboratories

BRE/FRS

As part of the BRE/FRS Forum related activities Goeff Cox collected and distributed to members of the working group a beautifully bound volume entitled "Collected Reports and Publications of the Fire Research Station on the Measurement of Thermal Radiation (1950-1990)". This volume contains thirty-seven individual documents from the Fire Research Station and represents, by far, the most extensive compilation of material dealing with heat flux measurements in fires.

Debbie Smith served admirably as the coordinator for the Group's Round Robin activity. She ensured that the heat flux gauges were available to each of the participating laboratories, provided guidance for performing the calibrations, and compiled and distributed the results of the activity.

FM Global

In addition to participating in the Round Robin, FM Global performed two additional Forum-related tasks. The first was supplying to the Working Group members a written description of their calibration facility. This detailed description was included with their summary of calibration results. Even though this system has been in use for many years, it had not previously been described.

The calibration facility at FM Global is designed to allow the response of heat flux gauges to be determined as a function of the angle at which the radiation strikes the gauge surface. Results of such measurements for the Schmidt-Boelter and Gardon gauges considered during the investigation were provided to the working group. Figure 11 shows the results for the Schmidt-Boelter gauge. As discussed above, it can be seen that the response agrees well with the ideal

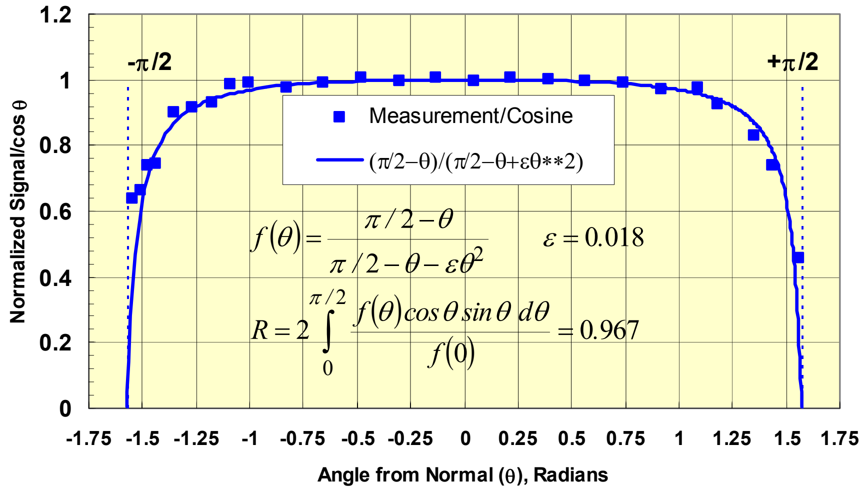


Figure 11. The measured response of the Schmidt-Boelter gauge is shown as a function of irradiation angle. The solid line represents an ideal cosine response.

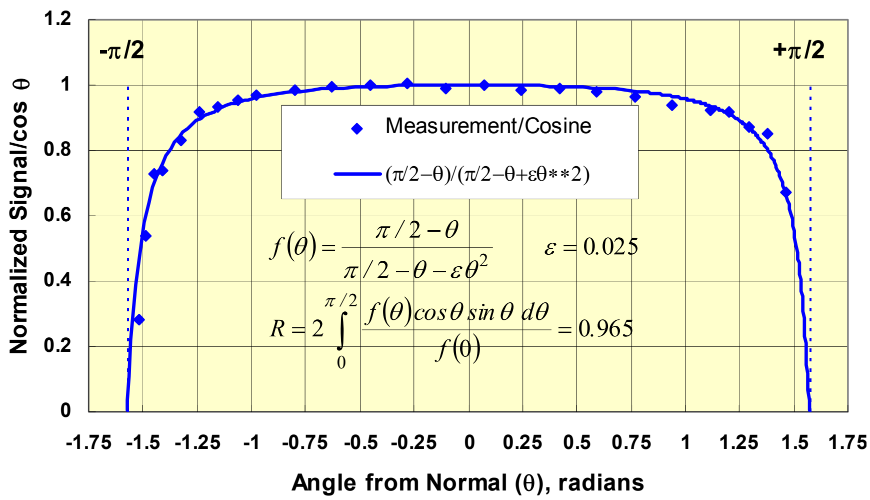


Figure 12. The measured response of the Gardon gauge is shown as a function of irradiation angle. The solid line represents an ideal cosine response.

cosine response until the angle from the vertical approaches 90°. Figure 12 shows the corresponding results for the Gardon gauge. The dependence on θ is similar to that observed for the Schmidt-Boelter gauge.

Table 4 summarizes the results for the two gauges. The dependence on angle is relatively small as indicated by the ratio of the hemispherical to normal absorptance. As discussed earlier, the results in the two figures indicate that the angular response of the gauges only deviates from the ideal cos(θ) dependence for angles that are nearly parallel to the surface.

Table 4. Summary of Results of Radiation Angle Dependence Measurements for the Gardon and Schmidt-Boelter Gauges

Gauge Type	Curve Fit	Adjustable Parameter, ε	Ratio of Hemispherical to Normal Absorptance
Schmidt-Boelter	$\dfrac{\frac{\pi}{2}-\theta}{\frac{\pi}{2}-\theta+\varepsilon\theta}$	0.018	0.967
Gardon	$\dfrac{\frac{\pi}{2}-\theta}{\frac{\pi}{2}-\theta+\varepsilon\theta}$	0.025	0.956

NIST

During the past year NIST/BFRL provided overall coordination for the working group. NIST also provided the two heat flux gauges used during the round robin and served as the pivot laboratory.

In the last few years NIST has been active in the development of approaches for characterizing heat flux gauges. A number of publications related to this work have been collected and were distributed to the working group as an optical CD entitled *Collected Reports and Publications by the National Institute of Standards and Technology on Heat Flux Gage Calibration and Usage* edited by W. M. Pitts and S. Regina Burgess. These manuscripts can also be accessed on the World Wide Web at http://www.bfrl.nist.gov/866/heatflux/.

The NIST/BFRL calibration system has been in use for over twenty-five years, but there had been no formal documentation. A written description was prepared and released as NIST Report of Test (FR 4014) entitled “NIST/BFRL Calibration System for Heat-Flux Gages” by W. M. Pitts, J. R. Lawson, and J. R. Shields. It is available on the optical CD described above.

A summary of the NIST/BFRL calibration for the round robin is available as a NIST Report of Test (FR 4015) entitled “Calibration of Heat Flux Gages for Forum Heat Flux Measurement Working Group Interlaboratory Comparison” by W. M. Pitts and J. R. Shields.

SINTEF

During the reporting period SINTEF completed an uncertainty analysis for their calibration system. A report prepared by Kjell Nygård, is included as Appendix B.

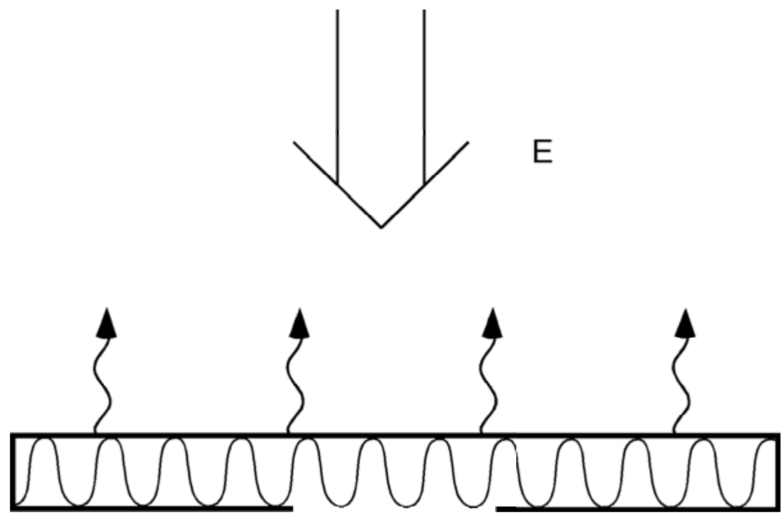


Figure 13. Incident radiation on Plate Thermometer.

SP

SP reported a number of activities that contribute to the Forum effort. One of these was the consideration of a slug calorimeter for heat flux measurements in a flooring flame spread test. Analysis indicated that the response time for the calorimeter was much too long to be useful for routine heat flux measurement. As an alternative, a plate thermometer was considered as a possible replacement. Extensive testing was performed. The results are summarized here.

Measurements with a Plate Thermometer were carried out in a Cone Calorimeter. Five different irradiation levels were used – 10kW, 20kW, 30kW, 40kW, 50kW – with the geometry shown in Figure 13. The temperature was measured every 5 seconds. Measurements were ended when the temperature of the plate-thermometer seemed to reach an asymptotic value.

The measurements were plotted as temperature reading versus time. The results were compared with a theoretical model. It turned out that there were differences between the measured and calculated curves.

The temperature calculated based on the model is

$$T_{s,2} = T_{s,1} + \frac{\Delta t}{dc\rho}[\varepsilon(q_r - \sigma T_{s,}^4) - h(T_{s,1} - T_\infty)],$$

where $T_{s,2}$ is the next calculated temperature, $T_{s,1}$ is the present temperature, Δt is the time step (5 s), d is the thickness of the plate (0.001 m), c is the specific heat, ρ is the density (7850 kg/m^3), ε is the emissivity (0.9), q_r is the irradiation level, σ equals 5.67×10^{-8}, h is the convective heat transfer coefficient, and T_∞ is the ambient temperature.

The variation of specific heat c is calculated using Eurocode 3. For various ranges of plate thermometer temperature, T_s, c is given by

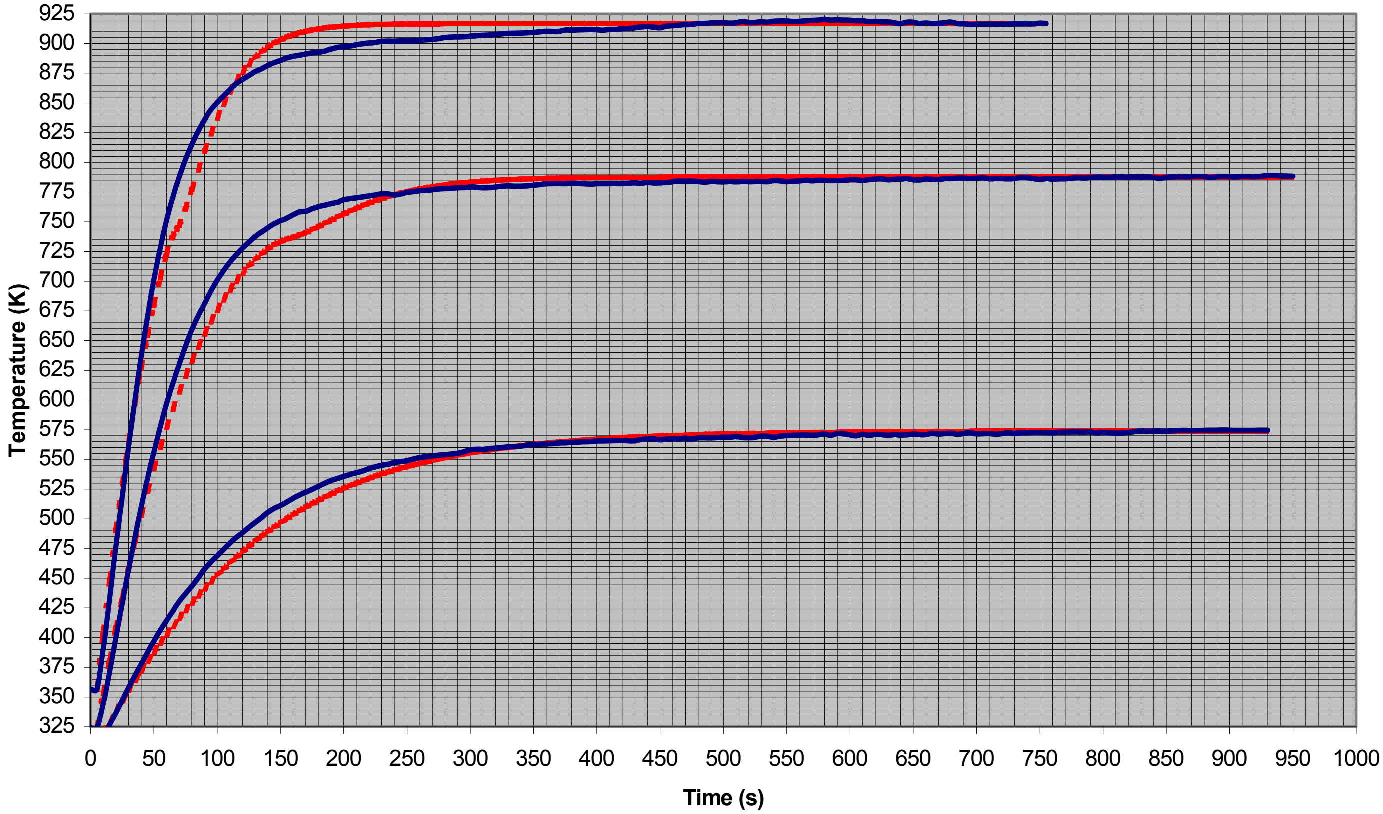


Figure 14. Time-temperature relation of calculated and measured Plate Thermometer temperature at incident heat radiation levels of 10 kW/m², 30 kW/m², and 50 kW/m².

$$c = 425 + 7.73\times10^{-1} T_s - 1.69\times10^{-3} T_s^2 + 2.22\times10^{-6} T_s^3 \quad \text{(J/kg K)} \quad \text{for } 0\ ^\circ\text{C} \le T_s < 600\ ^\circ\text{C},$$

$$c = 721 + \frac{5371}{738 - T_s} \ \text{J/kg K} \quad \text{for } 600^\circ\text{C} \le T_s < 735\ ^\circ\text{C},$$

$$c = 605 + \frac{7624}{T_s - 731} \ \text{J/kg K} \quad \text{for } 735\ ^\circ\text{C} \le T_s < 900\ ^\circ\text{C},$$

and

$$c = 650 \ \text{J/ kgK} \quad \text{for } 900^\circ\text{C} \le T_s < 1200\ ^\circ\text{C}.$$

The values of the convective heat transfer coefficient h were chosen so that the calculated highest value (final value) would match the measured highest value of temperature for the same irradiation values. For the measured values shown in Figure 14 the convective heat transfer coefficients were chosen as 2.15 kW/(m^2 K), 2.0 kW/(m^2 K), and 1.68 kW/(m^2 K) for incident levels of 10 kW/m^2, 30 kW/m^2, and 50 kW/m^2, respectively.

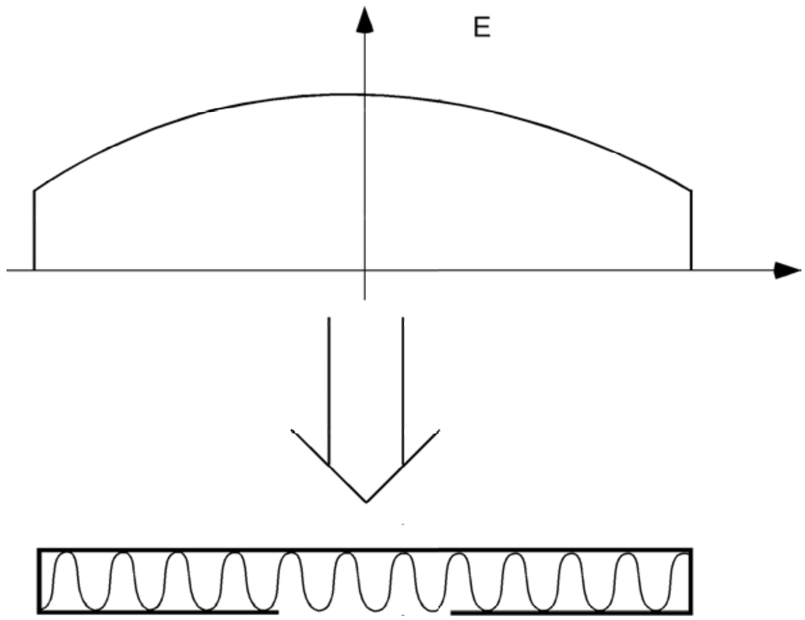


Figure 15. Distribution of incident heat radiation from cone calorimeter.

As one can see from the graph, the calculated curve for the temperature stabilizes much earlier than it does in reality. During intermediate time periods the calculated and measured curves do not match at al.

Better results might be obtained if a more accurate, i.e. a non-linear, model for the convective heat transfer was employed. However, the shorter “time constant” experienced for the calculated temperatures can probably be explained by the Plate Thermometer receiving a non-uniform incident heat flux such as that shown in Fig. 15. The calculation model does not consider two-dimensional effects.

This study was carried out to find out whether it was possible and practical to use the PT for very simply controlling the incident heat radiation level in the Cone Calorimeter. The results indicate that the time constant for the plate is probably too long as the result of an uneven irradiance level in the cone calorimeter. A smaller and thinner plate may therefore have an improved performance.

The accuracy of measured incident flux level will of course depend very much on controlling the emissivity of the plate, as the measured flux will depend directly on the that value. If properly treated and handled it is believed that this is possible, but further work is needed.

SP also continued its development efforts of the Gunners' heat flux gauge as part of their participation in the European HFCAL project. This device is an ellipsoidal radiometer that has been developed by Dr. Nils-Erik Gunners in cooperation with SP. During the reporting period an improved version was fabricated and assembled. The performance of the completed radiometer will be tested shortly. Earlier work on a prototype indicated that the angular response at angles between 20° and 90° (based on the normal) was very nearly that expected based on an ideal cosine curve, while the response at the angles near the normal was somewhat higher. Results for the improved version should be available shortly.

State Key Laboratory of Fire Science

The following report was submitted by Wang Xishi.

During the reporting period many efforts have been conducted. Substantial progress has been made on the development of a new system for heat flux gauge calibration. As part of this effort some commercial Gardon-type gauges were calibrated relatively using a standard SiC lamp in order to help analyze the stability of the whole system, including the gauges, voltage amplifier, the A/D board, etc. A second effort was designed to investigate the relative response of Gardon type gages to heat fluxes from fires under varying conditions, especially fires with a screen and fires with water mist applied. The goal is to allow measurements of heat flux in these difficult environments. Heat fluxes from fires with different fuels were also compared.

Our future work will focus on: (1) continued development of a system for heat flux gauge calibration; (2) development of new methods for heat flux measurement, for example, use of an uncooled micro-optomechanical sensor; and (3) heat flux measurements and calibrations in standard flammability apparatuses (e.g., cone calorimeter) using Gardon gauges.

IV. Discussion with HFCAL Team Members

On October 3 the coordinator for the Forum Heat Flux Measurement Working Group attended a meeting of the members of the European Union Project on Improving Heat Flux Calibration for Fire Laboratories (HFCAL). The member laboratories of HFCAL are LNE (France), SP (Sweden), TNO (The Netherlands) and VTT (Finland). HFCAL has many of the same general goals and activities as the Forum effort. The meeting was designed to be an exchange concerning activities in the two activities with consideration of approaches for limiting duplication and maximizing effectiveness. Roughly one half hour presentations were made concerning each activity. This was followed by additional informal discussion and information exchange. Both organizations committed to further discussions within their activities to explore mutual studies.

V. Recommendations

Based on work up do now, the working group provides the following recommendations concerning heat flux gauge calibration.

1. Every Forum laboratory should follow British Standard BS6809:87 that recommends maintaining *three* reference gages to ensure the stability of a calibration facility.

2. Forum laboratories should encourage the establishment of a commercial source(s) for cost-effective, routine calibration of heat flux gauges.

3. Periodic (perhaps every five years) round robins should be performed to ensure that interlaboratory comparability of heat flux gauge calibrations remain consistent over time.

VI. Next Steps

V1A. Repeated Round Robin

The Working Group believes that the round robin during the past year was a particularly useful exercise and provided a much better understanding of potential effects of differences in heat flux gauge calibration approaches. Due to a desire to verify the current findings and a desire by individual laboratories to address some concerns about their calibrations systems, the members agreed to repeat the round robin with two new gauges. The organization and management for the second round robin is to be unchanged from the first. In particular, "blind" calibrations will again be emphasized. Debbie Smith of BRE will once again serve as round robin manager.

There was general agreement that, subject to approval by the Forum, that the second round robin should be extended to include the current HFCAL laboratories that are not involved as well as any additional Forum laboratories who now wish to participate. The goal is to have the second round robin completed by the time of the next Working Group meeting. (see below)

VIB. Studies of Heat Flux Gauge Response in Standard Fire Test Configurations

Agreeing that the first objective of the working group will have been met at the completion of the second heat flux gauge calibration round robin, the members decided that it was time to initiate work on a second objective. It was mutually decided to begin collaborative research designed to address objective #4. As a result, each participating laboratory agreed to perform studies that "contribute to the understanding of total heat flux gauge measurements in standard fire test configurations by identifying the respective convective and radiative components." These studies are intended to be performed in the absence of flames.

Progress on these studies will be summarized during the next meeting of the working group (see below)

C. Next FORUM Heat Flux Measurement Working Group Meeting

The members of the Working Group agreed that their next meeting should take place in conjunction with the Seventh International Symposium on Fire Safety Science that is to be held at Worchester Polytechnic Institute in Worchester, MA on June 16-21, 2001. Tentative dates of June 13th and 14th, i.e., the Thursday and Friday before the ISFSS, were recommended.

Appendix A

Attendees

Participant	Laboratory	Email Address
Debbie Smith	BRE/FRS	smithda@bre.co.uk
John De Ris	FM Global	john.deris@fmglobal.com
William M. Pitts	NIST BFRL	wpitts@nist.gov
William Grosshandler	NIST BFRL	william.grosshandler@nist.gov
Kristen Opstad	SINTEF	kristen.opstad@civil.sintef.no
Ingrid Wetterlund	SP Swedish National Testing Laboratory	ingrid.wetterlund@sp.se
Ulf Wickstrom	SP Swedish National Testing Laboratory	ulf.wickstrom@sp.se

Appendix B

SINTEF Evaluation of Uncertainties When Calibrating Heat Flux Meters with a Spherical Furnace

By Kjell Nygård

When calibrating radiative heat flux meters with a spherical furnace, the uncertainties may be separated into two main categories. The first category is the uncertainty of the reference radiation and the second category is the uncertainty related to the heat flux meter. The convective contribution could have been placed in either of these categories, but the flux meter category was chosen since it does not involve radiation and also because it might be difficult to separate it from some of the other flux meter parameters. In fact, it is referred to as an "extra" contribution due to difficulties with separating the convective effect from others.

When quantifying uncertainties in this document, all uncertainties are expressed with a significance level of 95%.

1. Primary Black Body Reference Radiation Uncertainty Evaluation

Calibration of heat flux meters using a spherical furnace with a small opening is normally considered calibration by a primary reference. The radiation in this opening is defined closely by the temperature of the inside surface and the Stefan Bolzman equation. Provided that the furnace is well insulated and has a homogenous surface temperature, the only significant uncertainty is connected with the measurement of the inner surface temperature.

1.1. Defining furnace thermocouple temperature measurement uncertainties

1.1.1. Thermocouple calibration uncertainty

In order to measure temperatures with thermocouples, it is necessary to make the thermocouple output signal traceable to the international temperature standards as defined in ITS90. This means that the thermocouple has to be calibrated, and its deviation and uncertainty has to be quantified. If the calibration has been performed with sufficiently low uncertainty, using a correction polynomial can increase accuracy.

SINTEF has been achieving traceable thermocouple calibration uncertainties, including correction polynomial, of about 1.2 °C (temperature range 0 °C to 1100 °C).

1.1.2. Thermocouple ageing uncertainty

When thermocouples are used their response normally changes some as a function of time, temperature, and other influences. We call this ageing and the change is normally different at different temperatures. The change is usually larger at higher temperatures than at the lower end. For example after about 30 hours of use a typical uncertainty increase might be 0.5 °C + 0.001 × temperature.

1.1.3. Measurement system uncertainties

The thermocouple measurement system also contributes to the overall uncertainty with several sources.

- cold junction uncertainty. This uncertainty is normally less than 0.5 °C
- resolution and AD conversion uncertainty. Normally less than 0.1 °C
- conversion from volt to °C. Normally less than 0.1 °C
- standard deviation of measurement average (stability). Normally less than 0.1 °C

1.2. Defining influences on the thermocouple

1.2.2. Cold air draught influence on the thermocouple

If a thermocouple is placed inside the furnace, it will measure the temperature of itself and not directly the wall temperature. Cold air from the opening or air cooled by the flux meter might circulate up to the thermocouple and reduce its temperature by a small amount. The farther away from the opening and the closer the thermocouple is to the wall, the smaller this influence will be.

1.2.3. Difference in "view" of opening for furnace surface and the thermocouple

The opening might be "seen" by the thermocouple and reduce its temperature by a small amount due to the fact that the opening is not radiating heat. The farther away from the opening and the closer the thermocouple is to the wall, the smaller this influence will be. Convection will reduce this effect. On a small sphere at the cavity center, average radiation is 1.5 % less than walls due to the Ø49 mm hole area. If the opening is closed and insulated with only the Ø26 mm flux meter entering the furnace, then the average radiation on a small sphere at the cavity centre is 0.4 % less than the walls.

1.3. Furnace cavity wall temperature homogeneity

Provided that the furnace is well insulated and that the heating elements are evenly distributed then the furnace cavity surface temperature should become homogenous. This has been optically confirmed by looking inside the operating furnace without seeing any color deviations.

This uncertainty is unknown so far. In our opinion this uncertainty regarding temperature differences between different significant areas should be less than 1 °C. This means that if we measure the inside surface temperature at one location, this temperature should be representative of the average of the whole surface within 1 °C.

2. Heat Flux Meter Related Uncertainties

2.1. When referring to calibration of flux meters it is necessary to define a radiation reference temperature. This is the body temperature of the flux meter. At this temperature the flux meter is in thermal balance with the surroundings. The flux meter is emitting and receiving the same amount of radiation. At this temperature the flux meter has zero output voltage. It must be noted that although the flux meter has zero output, this does not mean that the incident radiation is zero. It only means that the radiation in and out are in balance and that the surroundings are at the same temperature as the flux meter.

2.2. When referring to the calibration of flux meters it is necessary to define the sensitivity related to a specified view angle because the sensitivity is angle dependent. This angle dependence varies somewhat for different flux meters and for different types of flux meters. In order to compare flux meters calibrated at different view angles one has to know both flux meter angle dependencies and their corresponding uncertainties.

2.3. The angle dependence and emissivity vary as the flux meter sensor coating ages. The total reflection angle increases with the smoothness of the coating. This means that one also has to define the coating status and include coating uncertainty to do a comparison of flux meters.

2.4. The output voltage of a flux meter is small, and the signal measurement uncertainty should be included.

2.5. The flux meter response may not be completely linear, and linearity cannot be assumed without measurements to support it. The linearity uncertainty must be quantified.

2.6. The total reflection angle increases with the smoothness of the coating. Since the flux meter doesn't accept input until the input angle is above horizontal, the opening doesn't influence the flux meter input radiation. The flux meter "sees" only the furnace cavity surface.

2.7. Due to the elevated air temperature inside the furnace cavity, the flux meter receives convective energy. This convective contribution can be reduced by buffering the flux meter with cold air, but it is not possible to remove it totally unless calibrating in vacuum. This means that one has to define the convection condition and include convection uncertainty in order to do a comparison of flux meter responses. At SINTEF several flux meters calibrated with different sources in our Black Body Furnace have been used. As the flux meter output readings exceed the calculated black body radiation at a given temperature, the difference has been interpreted mainly as the convective part of the flux meter input. The magnitude of this "extra" component varied with the flux meter reference calibration and has been averaged and expressed by a 4^{th} degree polynomial. This is not a totally satisfactory traceable uncertainty evaluation, but at the moment it is the best possible way. In order to quantify this convective contribution with the lowest possible uncertainty, the flux meter would have to be calibrated in vacuum.

3. <u>Summary of Uncertainties</u>

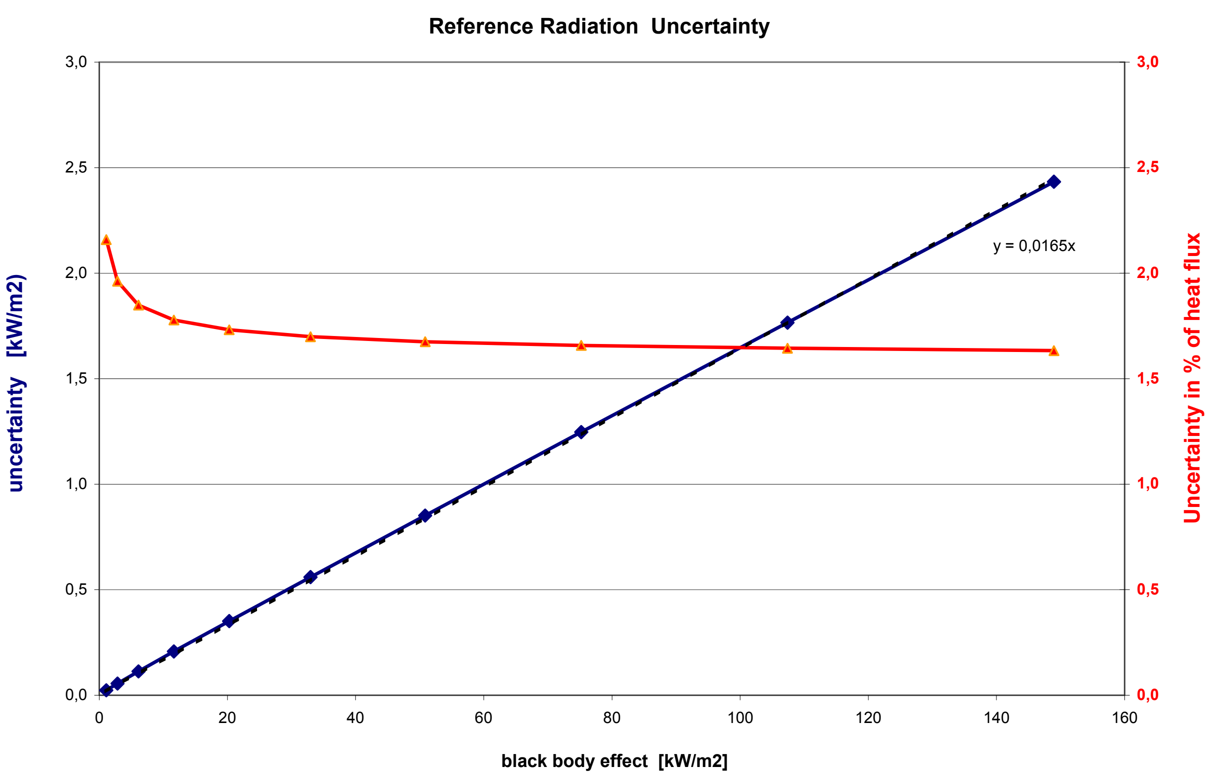
This section demonstrates the uncertainty analysis for the calibration of the round robin heat flux gauges by SINTEF using the facility shown in Fig. 4.

3.1. Summary of reference radiation uncertainties

Primary Black Body reference temperature uncertainties evaluation:

Furnace temperature [°C]	100	200	300	400	500	600	700	800	900	1000
black body radiation, kw/m2	1,10	2,84	6,12	11,64	20,26	32,96	50,85	75,20	107,40	148,97

	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2	kw/m2
tc signal measurement, resolution	0,001	0,00	0,00	0,01	0,01	0,02	0,02	0,03	0,04	0,05
tc signal measurement, stdev of measurement average (stability)	0,001	0,00	0,00	0,01	0,01	0,02	0,02	0,03	0,04	0,05
tc signal measurement, cold junction uncertainty	0,006	0,01	0,02	0,03	0,05	0,08	0,10	0,14	0,18	0,23
tc calibration uncertainty including correction formula	0,014	0,03	0,05	0,08	0,13	0,18	0,25	0,34	0,44	0,56
tc ageing since last calibration (example for about 30 hours of use)	0,007	0,02	0,03	0,06	0,11	0,17	0,25	0,37	0,51	0,70
tc signal measurement, conversion from volt to °K	0,001	0,00	0,00	0,01	0,01	0,02	0,02	0,03	0,04	0,05
cold air draught influence (guess)	0,001	0,00	0,01	0,01	0,03	0,05	0,07	0,11	0,16	0,23
Difference in "view" of opening for furnace surface and the thermocouple due to Ø49mm hole area. By moving the tc higher inside the cavity this influence becomes smaller on tc.	0,016	0,04	0,09	0,17	0,30	0,49	0,76	1,13	1,61	2,23
Statistical sum of uncertainties presuming independent and normal distribution (2std) recalculated to % of radiation level	2,16	1,96	1,85	1,78	1,73	1,70	1,68	1,66	1,64	1,63



3.2 Heat flux meter related uncertainties

Spherical Furnace NBL-221 with fluxmeter NBL-1138

Evaluation of additional signal components (convection, unlinarity and other) as a function of temperature.

When measuring heat flux from a spherical furnace by inserting a fluxmeter, the total heatflux absorbed by the heatfluxmeter sensor is a sum of several components such as as radiation, convection,emissivity, fluxmeter ref.temp, fluxmeter unlinearity, angular influence and other.

When such a furnace has stabilised at a temperature it can be considered a "black body" +0,5% due to the 40mm hole. The main signal component is the "Black Body" radiation, which can be easily calculated by measuring the furnace temperature. Radiated flux from the fluxmeter is also easily calculated by measuring the fluxmeter body/water temperature. Angular influence can be eliminated when the whole 180° view angle is seeing the same temperature. Provided the fluxmeter emissivity is constant it will be a permanet part of the incident sensitivity. The convective contribution is some depependent of fluxmeter type. To measure the convective component one may use a calibrated and certified linear fluxmeter and measure total flux. The total additional signal is then the difference between total flux and radiative flux.

			Additional components 1		Additional components 2	
Furnace temperature	absolute black body radiation	total uncertainty in kw	average of Medtherm+ SP+NBL	33% 2std esimated uncertainty	ref Thermogage 1995	33% 2std esimated uncertainty
°C	kw/m2	kw/m2	kw/m2	kw/m2	**kw/m2**	kw/m2
25	**0**	0.01	**0**	1.0	**0**	1.0
100	**1**	0.02	**1**	1.3	**2**	1.6
200	**3**	0.06	**2**	1.6	**3**	2.1
317	**7**	0.11	**2**	1.8	**5**	2.5
448	**15**	0.20	**4**	2.2	**6**	2.9
528	**24**	0.25	**5**	2.6	**7**	3.3
599	**33**	0.34	**6**	3.0	**8**	3.6
699	**51**	0.45	**8**	3.7	**10**	4.4
779	**70**	0.57	**10**	4.4	**13**	5.2
839	**87**	0.67	**12**	4.9	**15**	5.9

convection 1	
_k0	**-0.4120**
_k1	**0.01908**
_k2	**-5.930E-05**
_k3	**1.027E-07**
_k4	**-4.575E-11**

convection 2, ref Thermogage	
_m0	**-0.8000**
_m1	**0.03409**
_m2	**-8.459E-05**
_m3	**1.082E-07**
_m4	**-3.4921E-11**